NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 1951

METHOD OF DETERMINING CONDITIONS OF MAXIMUM EFFICIENCY OF AN INDEPENDENT TURBINE-PROPELLER COMBINATION

By Marcus F. Heidmann

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
September 1949

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 1951

METHOD OF DETERMINING CONDITIONS OF MAXIMUM EFFICIENCY OF AN INDEPENDENT TURBINE-PROPELLER COMBINATION

By Marcus F. Heidmann

SUMMARY

The characteristics of a turbine and a propeller were investigated to determine the conditions of maximum-efficiency operation when utilized as an independent turbine-propeller combination. The procedure used to determine the conditions of maximum efficiency and the speed ratio between the turbine and the propeller is illustrated. This procedure involved the use of a method of matching turbines and propellers.

By the use of this method, the conditions for maximum-efficiency operation can be defined by turbine-inlet temperature, pressure ratio, and propeller speed for each flight condition. The relation between these parameters is adaptable to independent control of turbine-propeller speed when interaction between the turbine-propeller combination and the gas generator is either nonexistent or when the effects of interaction can be sufficiently damped.

INTRODUCTION

An independent turbine-propeller combination constitutes a component of an aircraft-propulsion system that may be used with any type of gas-generating unit supplying the necessary gas-energy conditions for the turbine. This component is independent in the sense that there is no mechanical drive between the gas generator and the turbine-propeller combinations. One of the characteristics of such a propulsion system is the absence of a fixed ratio between turbine-propeller speed and gas-generator speed. This characteristic can be utilized to realize efficient over-all performance by operating both the generator and the turbine-propeller combination at speeds resulting in maximum efficiency for any given power output. Operation along a curve of maximum-efficiency conditions is defined as maximum-efficiency operation.

An analysis of an independent turbine-propeller combination conducted at the NACA Lewis laboratory is presented herein. The speed ratio for maximum-efficiency operation and the resulting

control relation are determined over a range of turbine-inlet and flight conditions. The conditions for maximum-efficiency operation and the control of the turbine-propeller combination are discussed. The procedure used in the analysis involved the application of a method for matching turbines and propellers at various speed ratios.

In the analysis, the characteristics of a representative gas turbine and propeller were used. The speed ratio of the coupled turbine and propeller was assumed constant with no gearing losses and the outlet static pressure of the turbine was assumed to be equal to the ambient pressure.

METHOD OF ANALYSIS

Turbine and propeller characteristics. - The individual performance characteristics of the turbine and the propeller are shown in figures 1 and 2, respectively. For both the turbine and the propeller, a value of blade speed exists for each operating condition that defines operation at maximum efficiency. For the turbine, as shown in figure 1, maximum-efficiency operation is defined by the maximum efficiencies for each pressure ratio. Maximum-efficiency operation of the propeller at any flight velocity (fig. 2) occurs at the minimum-horsepower conditions at constant thrust. In the turbine, each maximum-efficiency condition at constant thermal dynamic input and altitude determines only one value of speed and horsepower. Similarly, for the propeller at constant flight velocity and altitude, maximum-efficiency operation is defined by a relation of speed and horsepower. It is improbable, however, for a turbine-propeller combination operating with a fixed speed ratio, that these relations of speed and horsepower will coincide for all operating conditions. Actually, for any value of transmitted horsepower, the speed for maximum-efficiency operation will occur somewhere between that defined by only the turbine and the propeller.

Determination of maximum combined efficiency. - The maximum-combined-efficiency conditions can be obtained and most simply illustrated by representing both turbine and propeller characteristics on the same coordinate systems. The coordinates selected were blade speed and horsepower divided by altitude-density ratio. In making the representation, all the parameters were calculated as percentage of reference values and the reference values of turbine and propeller horsepower were made equal to each other. With this representation, the turbine characteristics at altitudes of sea level and 40,000 feet are shown in figure 3 and the propeller characteristics for flight velocities of 200, 400, and 600 miles per hour are shown in figure 4.

In the independent turbine-propeller combination, the horsepower of the turbine equals the horsepower of the propeller and the ratio of blade speeds is constant. Inasmuch as both figures 3 and 4 are presented on log-log plots, the characteristics resulting from coupling the turbine and the propeller could be obtained by superimposing the turbine characteristics on the propeller characteristics under the stated conditions. This superimposition is impossible, however, without a known speed ratio. The selection of a speed ratio is dependent on a number of factors and limitations that may be characteristic of the installation. In this analysis, the general case will be assumed in which a gas generator delivers gas at increasing pressure with increasing temperature. A speed ratio will be selected that compromises between the condition of maximum efficiency at low pressure ratio and temperature, and the condition of maximum efficiency at high pressure ratio and temperature for all the assumed flight conditions.

The best approximate over-all efficiency is obtained with a ratio of percentage turbine-blade speed to percentage propeller-blade speed of 2.4. With this percentage speed ratio, the characteristics of the coupled turbine and propeller are shown in figure 5 for flight velocities of 200, 400, and 600 miles per hour at altitudes of sea level and 40,000 feet.

<u>Control relation for maximum efficiency.</u> - Maximum-efficiency operating conditions can be obtained from figure 5 for each pressure ratio and temperature under the various flight conditions investigated. Maximum-efficiency operation is defined by the points of tangency of the temperature and thrust curves. From inspection, these points were obtained and plotted in figure 6, which shows the change of propeller-blade speed with turbine-inlet temperature for each pressure ratio and flight condition. All parameters required to define maximum-efficiency operation are presented in figure 6. This figure indicates the parameters and the relation that may be incorporated into the design of a control for the turbine-propeller combination.

RESULTS AND DISCUSSION

For the propeller and turbine data used and the flight conditions investigated, figure 6 shows the effect of flight velocity and altitude on the relation of parameters for maximum-efficiency operation to be small. In reality, turbine operating conditions influence the maximum over-all efficiency to a greater extent than the propeller operating conditions. Flight velocity and altitude, which contribute to propeller performance, therefore had little effect on the curves of figure 6.

The dependence on turbine characteristics may be attributed to the fact that the angle of attack of the propeller may be adjusted by means of a pitch-angle change, whereas such an adjustment is impossible for the turbine. As a result of the small effect of flight conditions on the maximum-efficiency relation, a single curve was drawn through all the points at each pressure ratio. The trend in propeller characteristics with decreasing velocity indicates that such a generalization below a flight velocity of 200 miles per hour may be impossible.

1123

At a flight velocity of 600 miles per hour, only the high-power conditions were considered. The propeller at low power was extremely inefficient and, inasmuch as maximum-efficiency operation for low power at 600 miles per hour has little practical application, this power range was not investigated.

The performance results of this analysis are applicable only to the propeller and turbine data assumed. An extensive analysis of the problem may indicate a greater effect of flight condition on the relation presented in figure 6. The propeller characteristics assumed (fig. 2) represent the low-speed characteristics of a propeller and were used to illustrate the method of obtaining maximum-efficiency operating conditions. Other propeller and turbine data may lead to a different relation of the parameters. The general method, however, is applicable to any combination of turbine and propeller data and the same parameters will determine the desired operating condition.

The procedure used to obtain the operating conditions for highest over-all efficiency involved the use of a method of matching turbines and propellers. In this analysis, a turbine and a propeller of known power ratings were assumed. From the blade-speed ratio that was obtained, a rotary speed ratio may be calculated dependent on the diameters of the turbine and the propeller. The characteristics of a propeller of a specific diameter are shown in figure 2. A specific turbine diameter, however, is not implied by its characteristics in figure 1. The rotary speed ratio is therefore dependent on turbine diameter. The selection of this ratio is left to the designer providing that in selecting a turbine diameter, hub-to-tip diameter ratio of the turbine remains constant and stress and other design limitations are not exceeded. The method of matching is also applicable when using propeller characteristics corrected for propeller diameter. The propeller diameter can remain unevaluated until after the components are matched. This method of matching therefore provides a means of selecting a turbine diameter, a propeller diameter, and a gear ratio that will give performance most nearly approaching any specified performance.

Two general methods are possible for the control of turbine-propeller speed: The speed may be controlled independently of the gas-generator component or the control of the turbine-propeller and the generator may be interrelated. The method used is dependent on the characteristics of the complete propulsion system.

1123 With independent control of the turbine-propeller combination, the control is concerned only with the available power and flight conditions from which the desired operating condition is determined and no knowledge of the operating condition of the generator component is assumed. One important condition must be met, however, for satisfactory control by this method. It is necessary that interaction between the turbine-propeller combination and the gas generator is either nonexistent or that the effects of the combination can be sufficiently damped to allow a condition of stable equilibrium to be obtained. With interaction, a change in turbine-propeller speed will possibly, for example, alter mass flow through the propulsion system and thereby change the temperature, the pressure, and the power delivered by the generator component. The operating condition as determined from the available power will change and an additional change in speed is required again to obtain a desired operating condition. Such a condition of interaction could lead to completely unstable operation. A more complete analysis of interaction and its relation to the control is described in reference 1.

A control in which the turbine-propeller combination and the generator component are interrelated would consist of a system in which the turbine-propeller operation is scheduled in accordance with the operating condition of the generator. If the effect of interaction cannot be sufficiently damped, this type of control is required. Such a method of control can be investigated only through an analysis of the complete propulsion system.

The relation of parameters for maximum efficiency shown in figure 6 readily lends itself to the independent control of a turbine-propeller combination. In these curves, the relation between blade speed and temperature is substantially linear and the slope of the curve is approximately constant for all pressure ratios. Independent control requires the condition of either no interaction or of sufficient damping of its effects where interaction occurs. One method of obtaining no interaction is to design the system to maintain critical flow in the turbine nozzle of the turbine-propeller combination under all operating conditions. The turbine assumed in this analysis meets this requirement over a wide range of power conditions and it is assumed that a generator component delivering the desired available power can be developed.

From a measurement of turbine-inlet temperature and pressure ratio, the required propeller speed under any flight condition is determined as indicated in figure 6. One possible control system based on this relation would consist of a mechanism for changing the propeller-blade angle, the mechanism being actuated by an adjustable-speed governor for maintaining the propeller speed at a value determined by measured values of turbine-inlet temperature and the pressure ratio.

1123

SUMMARY OF RESULTS

From an investigation of an independent turbine-propeller combination, it was found that the conditions for maximum efficiency can be obtained by the use of a method of matching turbine and propeller characteristics. By the use of this method, maximum efficiency operation can be satisfactorily represented by a relation of turbine-inlet temperature, pressure ratio, and propeller speed for each flight velocity and altitude. The described relation is adaptable to independent control of turbine-propeller speed when interaction between the turbine-propeller combination and the gas generator is either nonexistent or where its effects can be sufficiently damped.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 18, 1949.

APPENDIX - SYMBOLS

The following symbols are used in the figures referred to in the analysis:

F propeller thrust, lb

hp horsepower

P_r ratio of turbine-inlet pressure to turbine-outlet pressure (total to static)

T turbine-inlet temperature, $^{\circ}R$

V flight velocity, ft/sec

v_p propeller-blade tip speed, ft/sec

v_t turbine-blade tip speed, ft/sec

w gas flow, lb/sec

β propeller-blade angle, deg

δ ratio of turbine-inlet pressure to sea-level ambient pressure

θ ratio of turbine-inlet temperature to sea-level ambient temperature

σ ratio of altitude density to sea-level density

REFERENCE

1. Boksenbom, Aaron S., and Hood, Richard: General Algebraic Method Applied to Control Analysis of Complex Engine Types. NACA TN 1908, 1949.

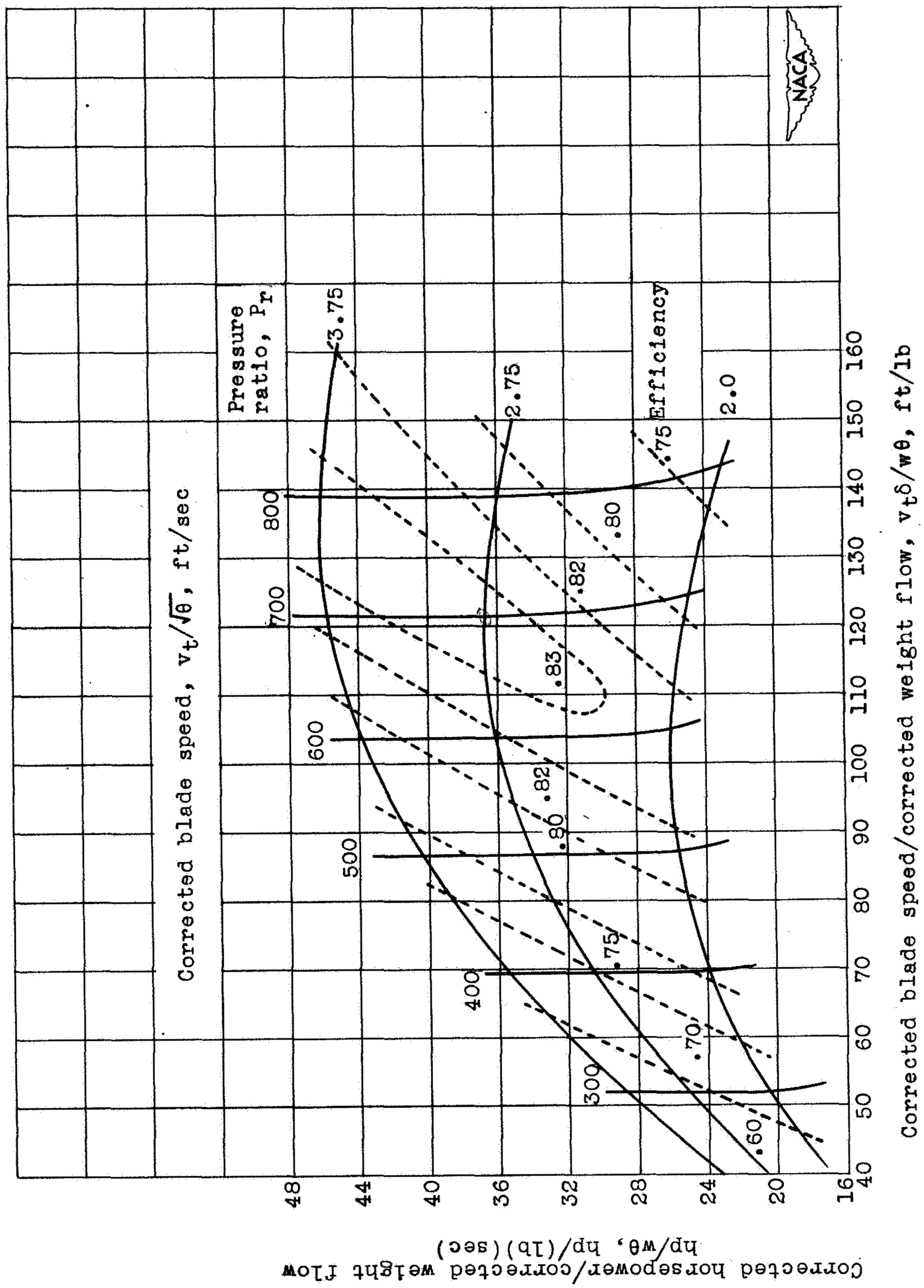


Figure 1. - Over-all turbine performance characteristics corrected for turbine-inlet pressure and temperature relative to NACA standard atmospheric conditions at sea level. (All symbols used on figures are defined in appendix.)

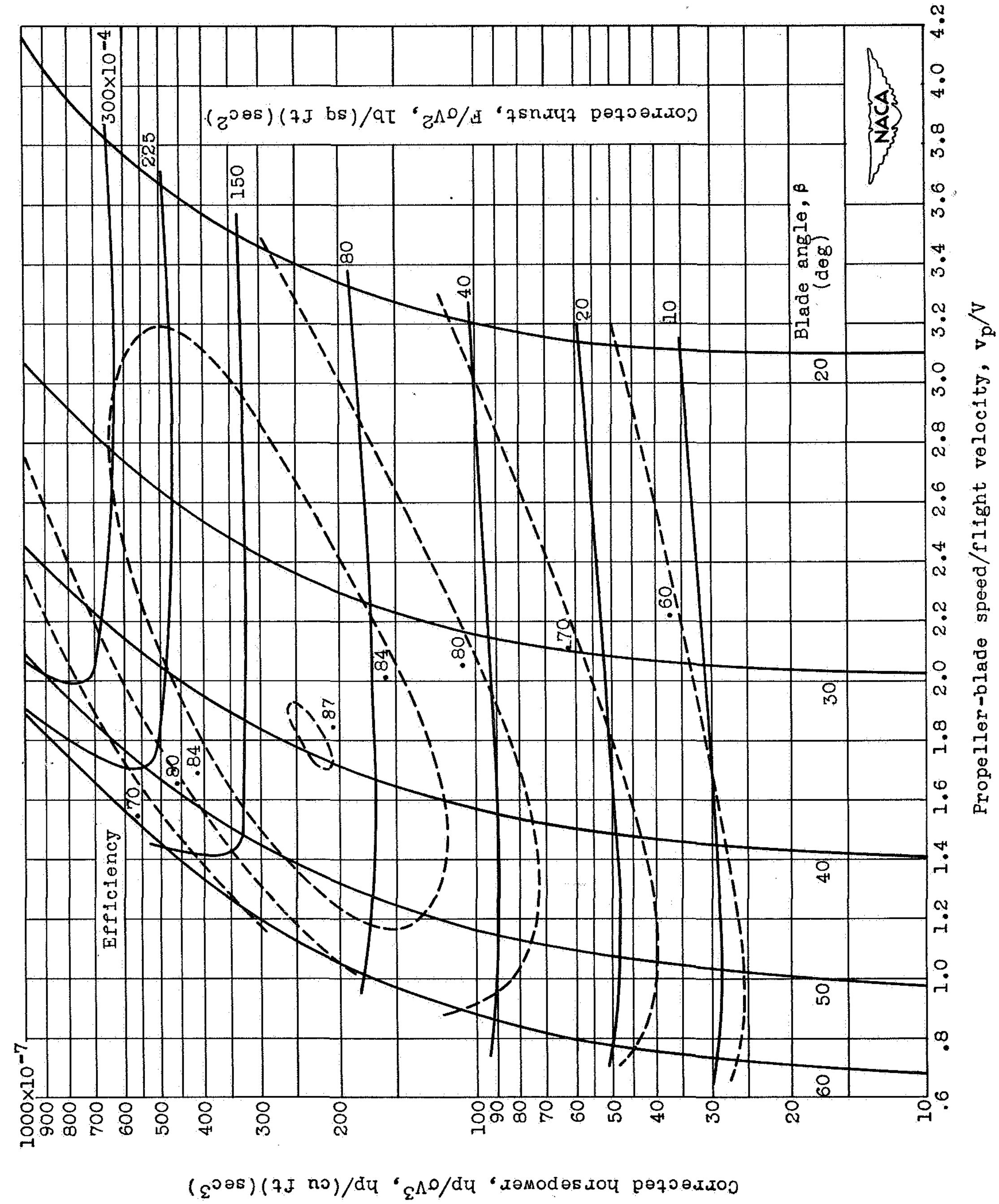


Figure 2. - Over-all propeller performance characteristics corrected for flight velocity and altitude.

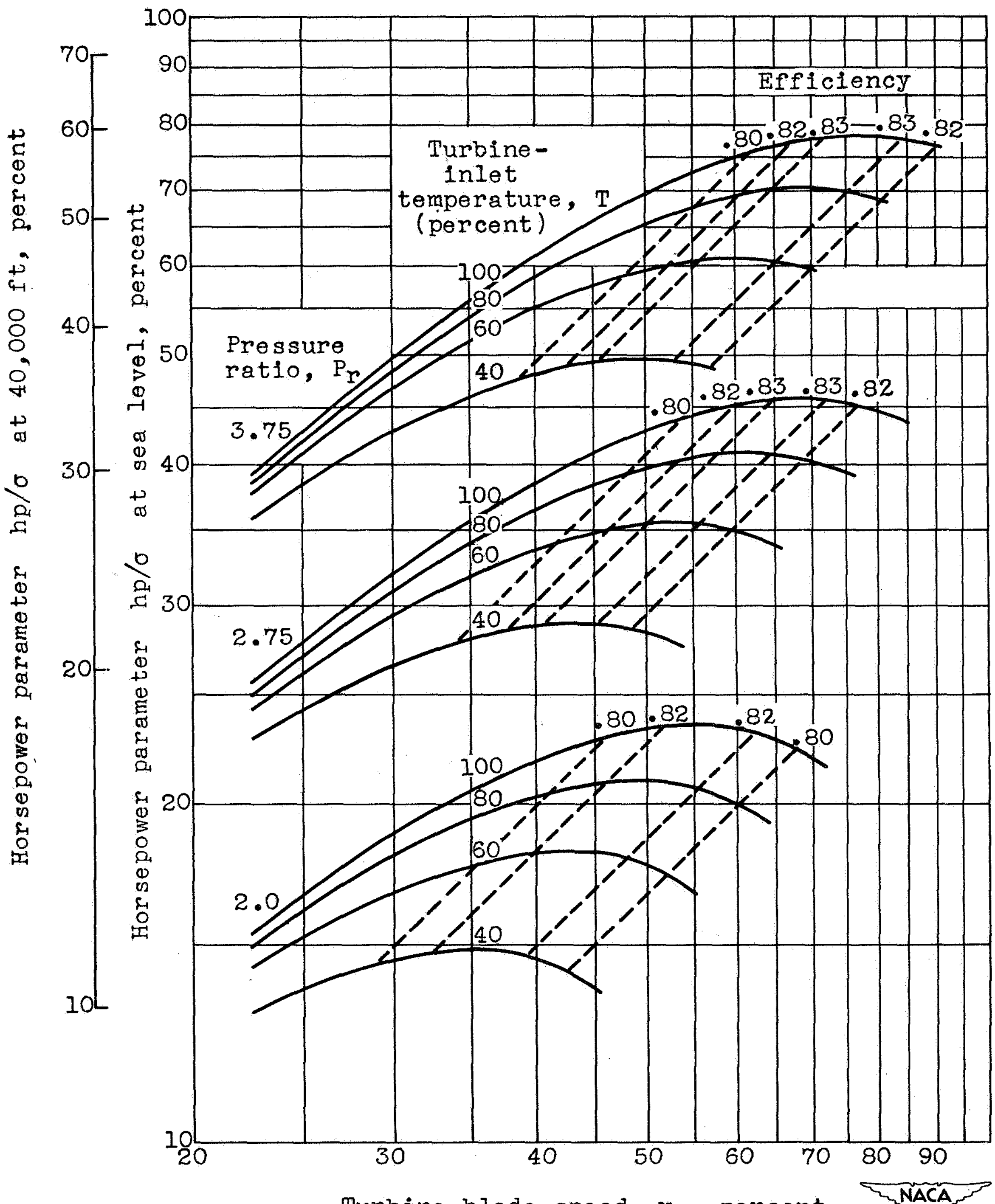
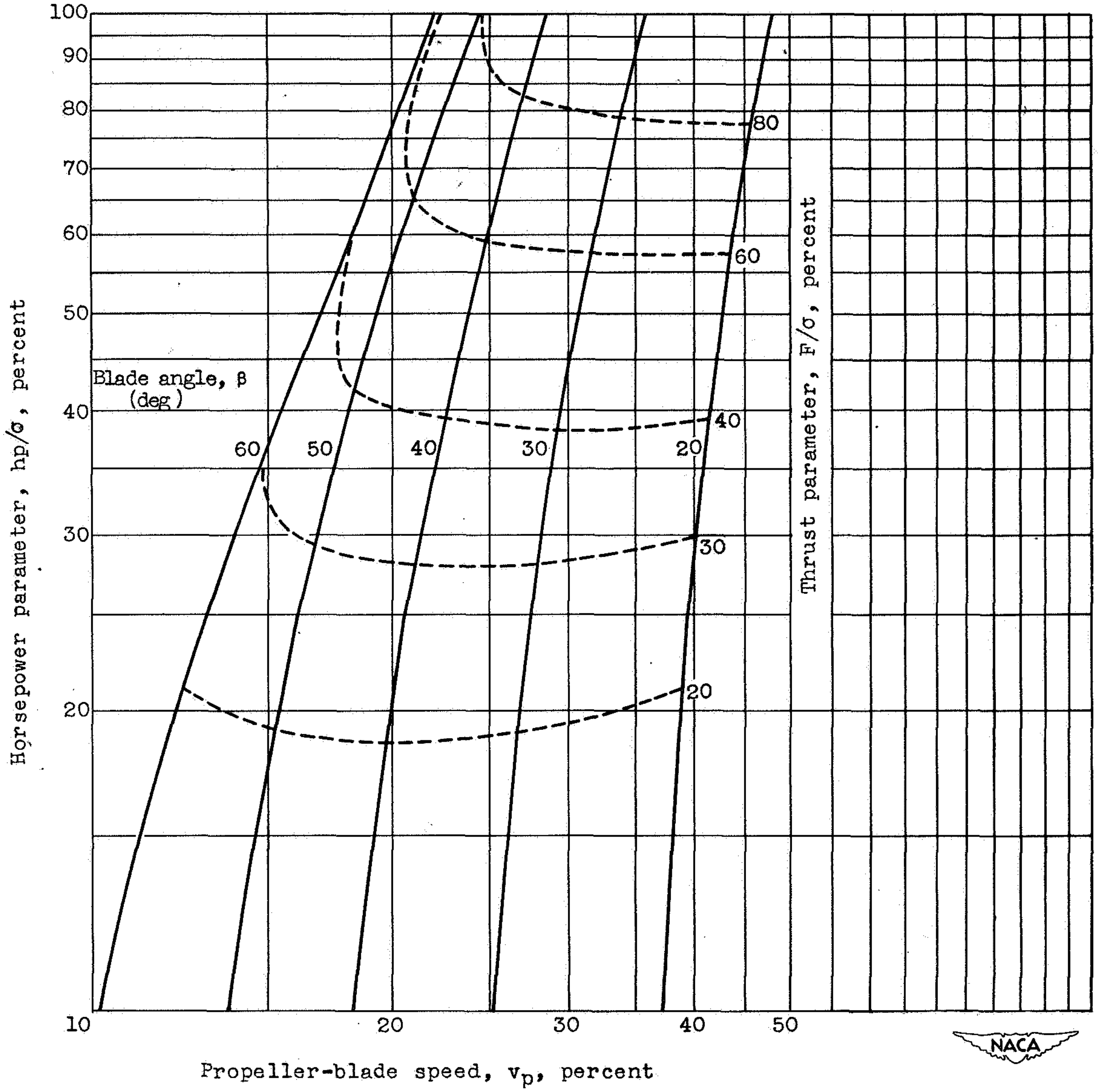


Figure 3. - Turbine characteristics of altitudes of sea level and 40,000 feet with expansion to atmospheric pressure.

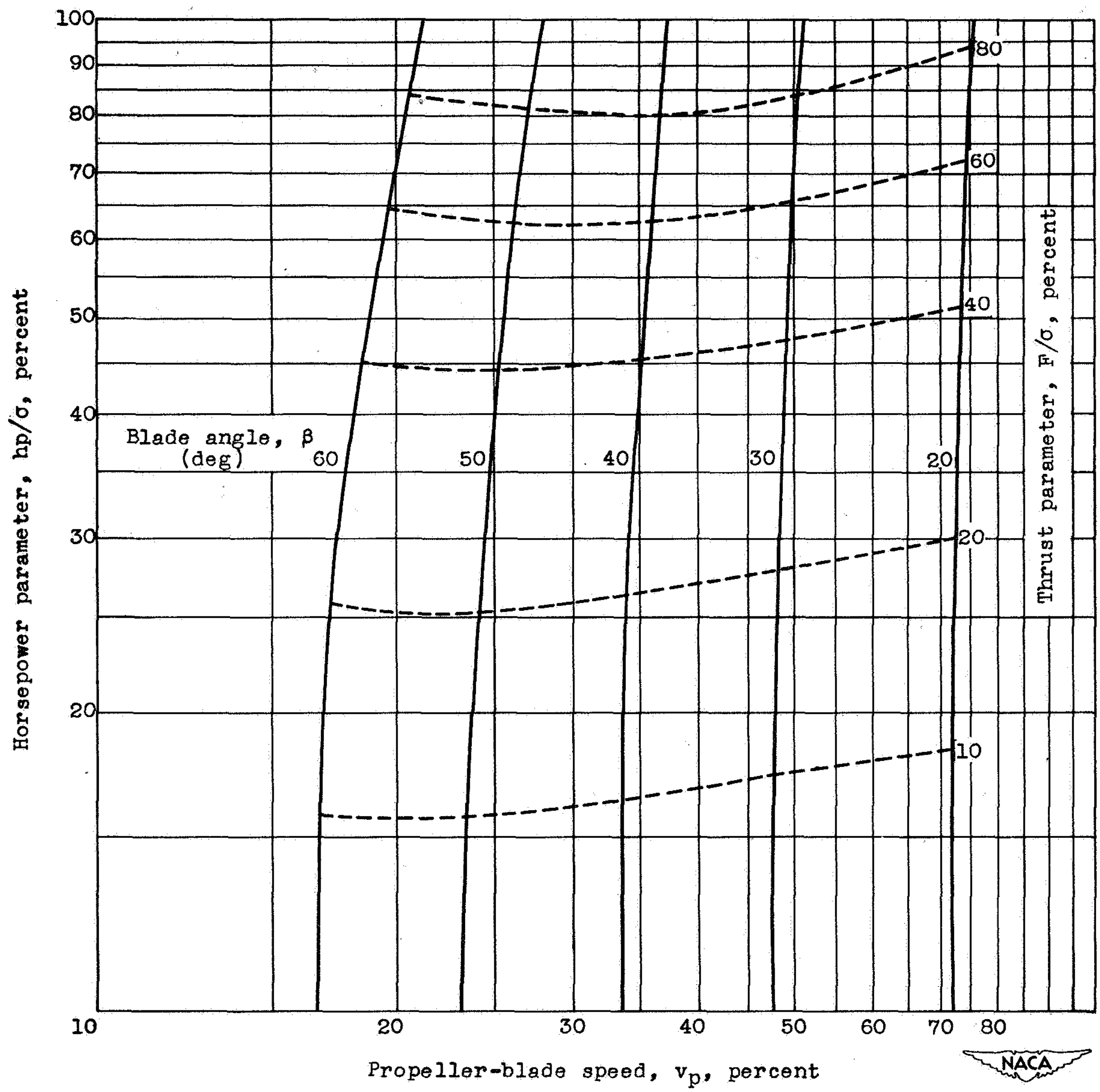
1123



(a) Flight velocity, 200 miles per hour.

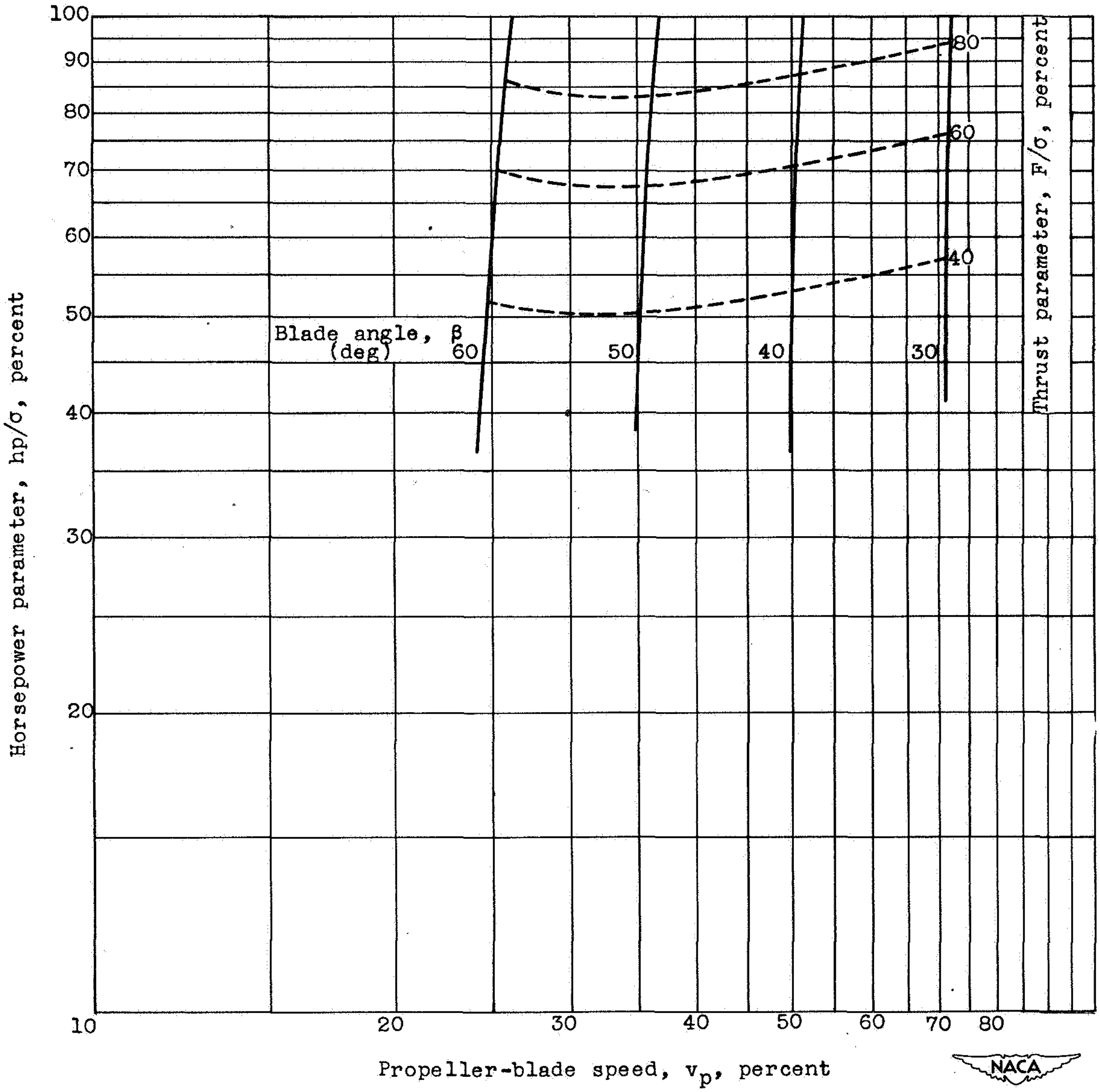
Figure 4. - Propeller characteristics at constant flight velocity.

1123



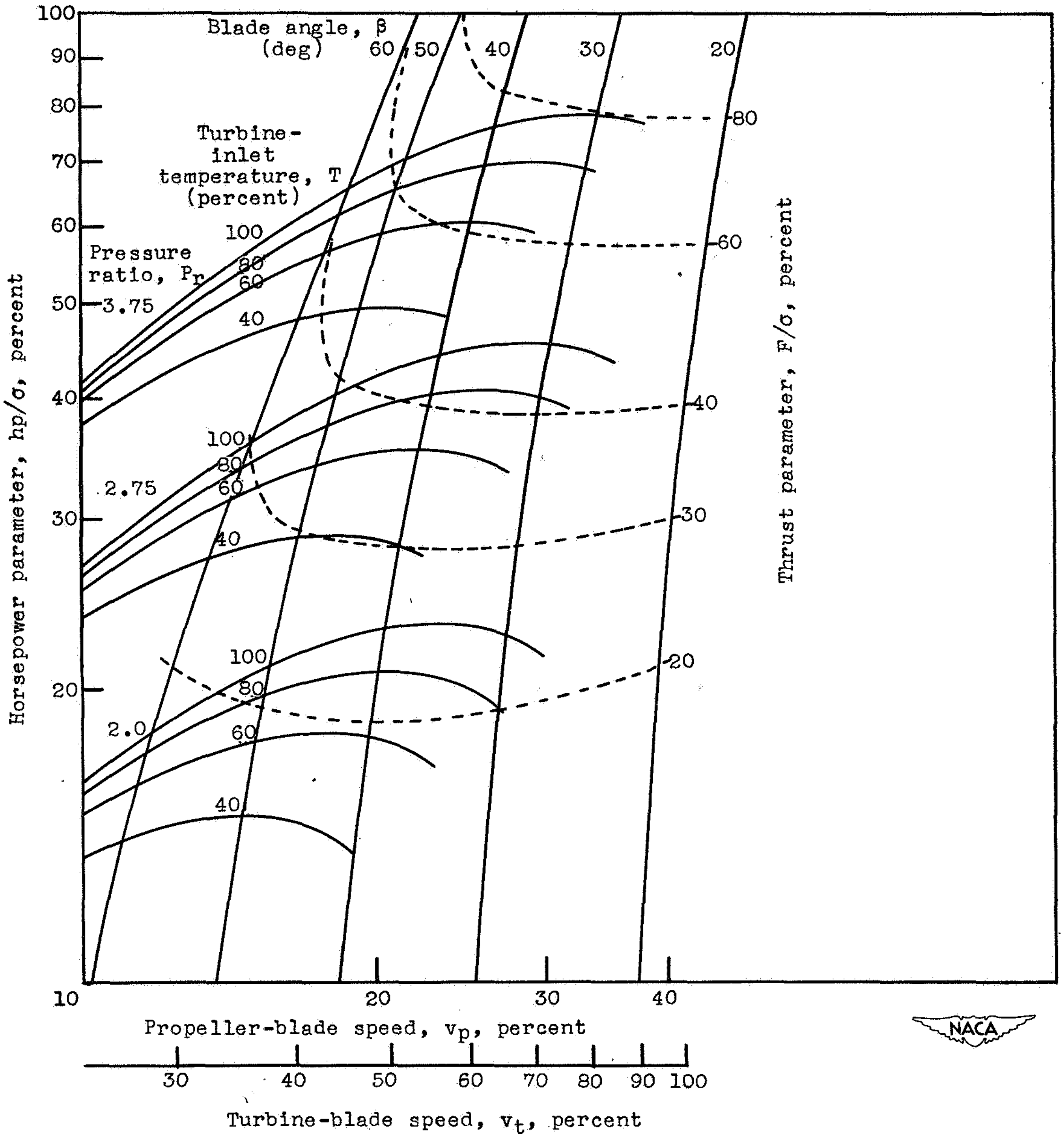
(b) Flight velocity, 400 miles per hour.

Figure 4. - Continued. Propeller characteristics at constant flight velocity.



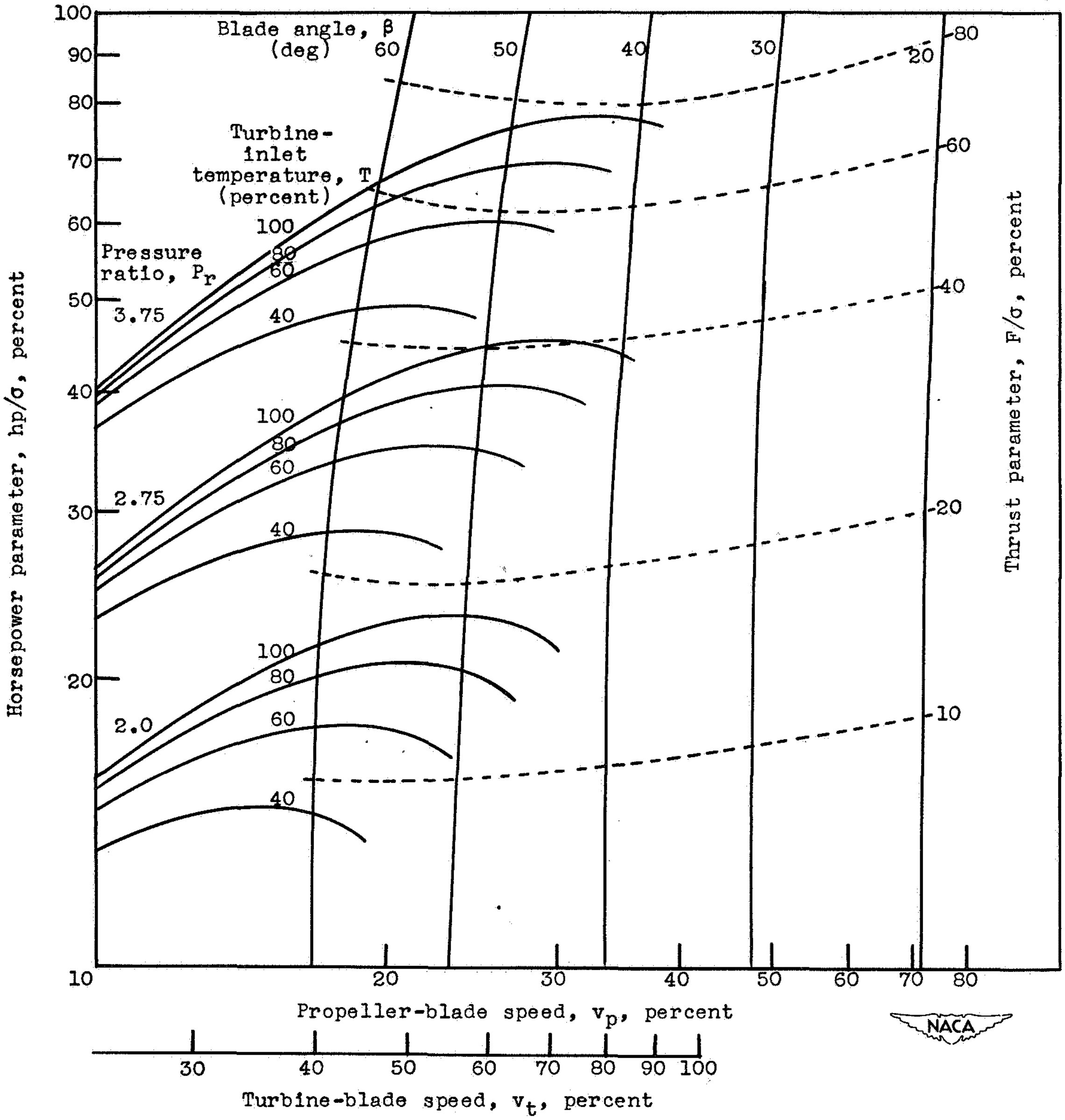
(c) Flight velocity, 600 miles per hour.

Figure 4. - Concluded. Propeller characteristics at constant flight velocity.



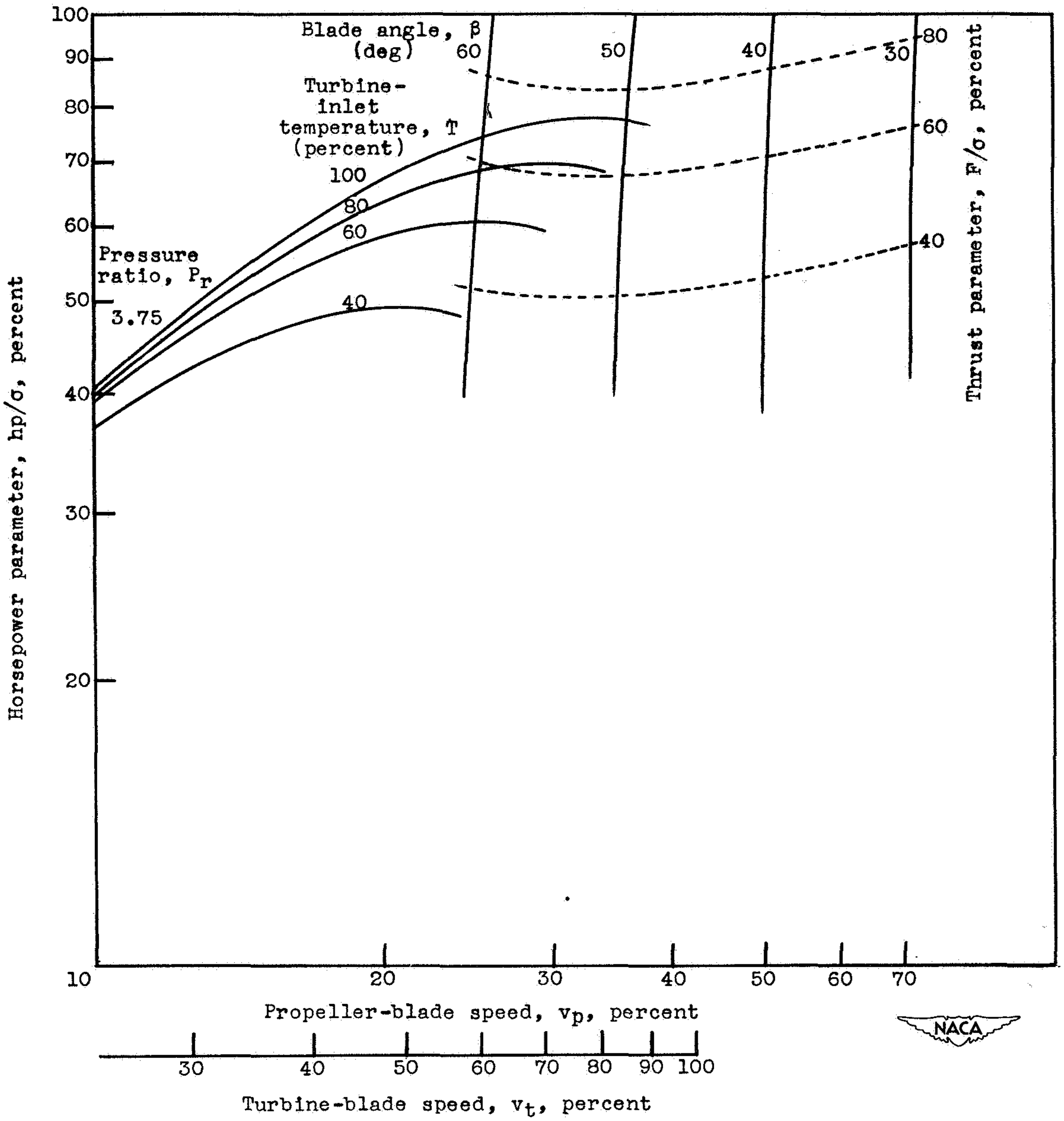
(a) Altitude, sea level; flight velocity, 200 miles per hour.

Figure 5. - Performance characteristics of independent turbine-propeller combination.



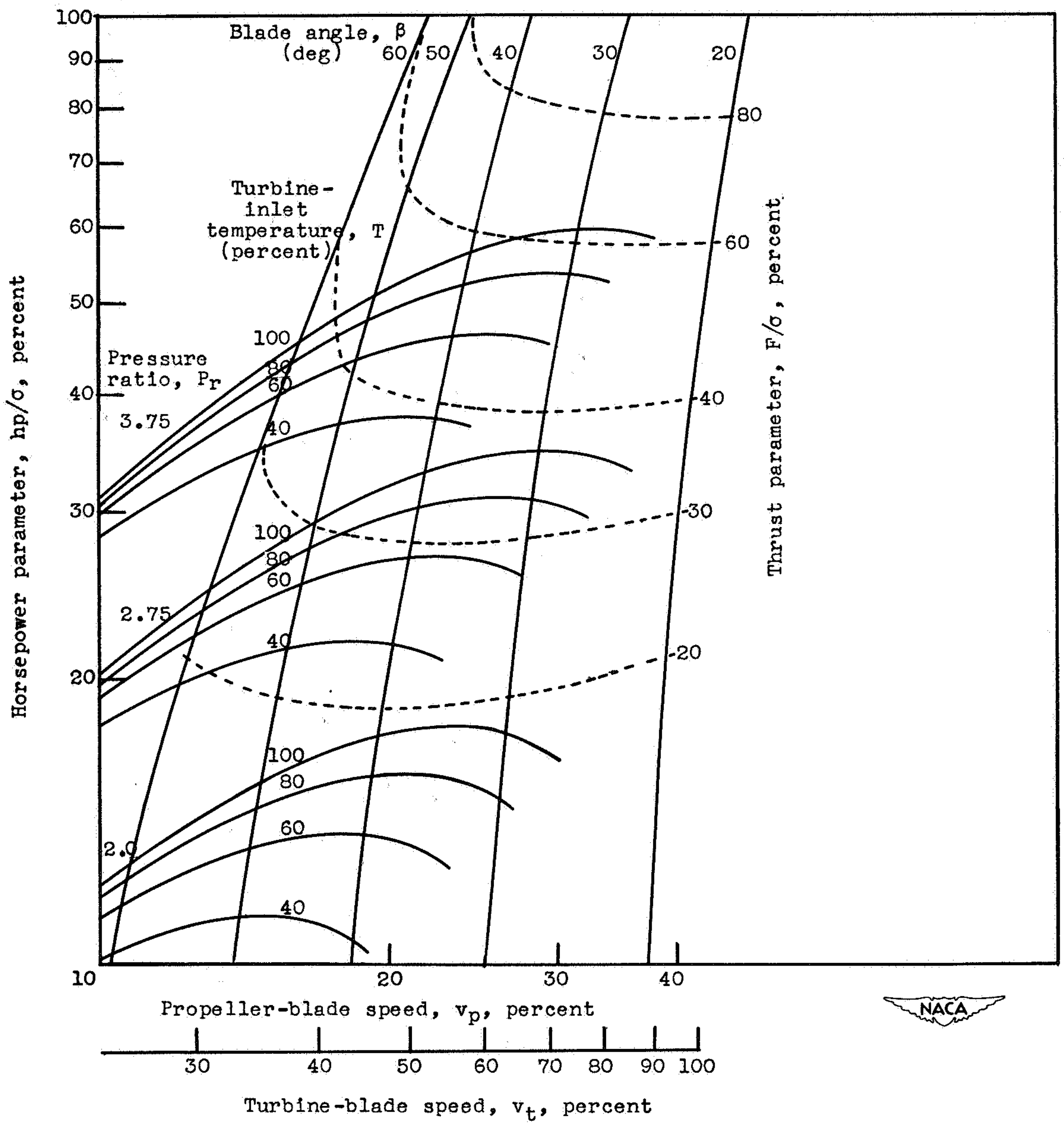
(b) Altitude, sea level; flight velocity, 400 miles per hour.

Figure 5. - Continued. Performance characteristics of independent turbine-propeller combination.



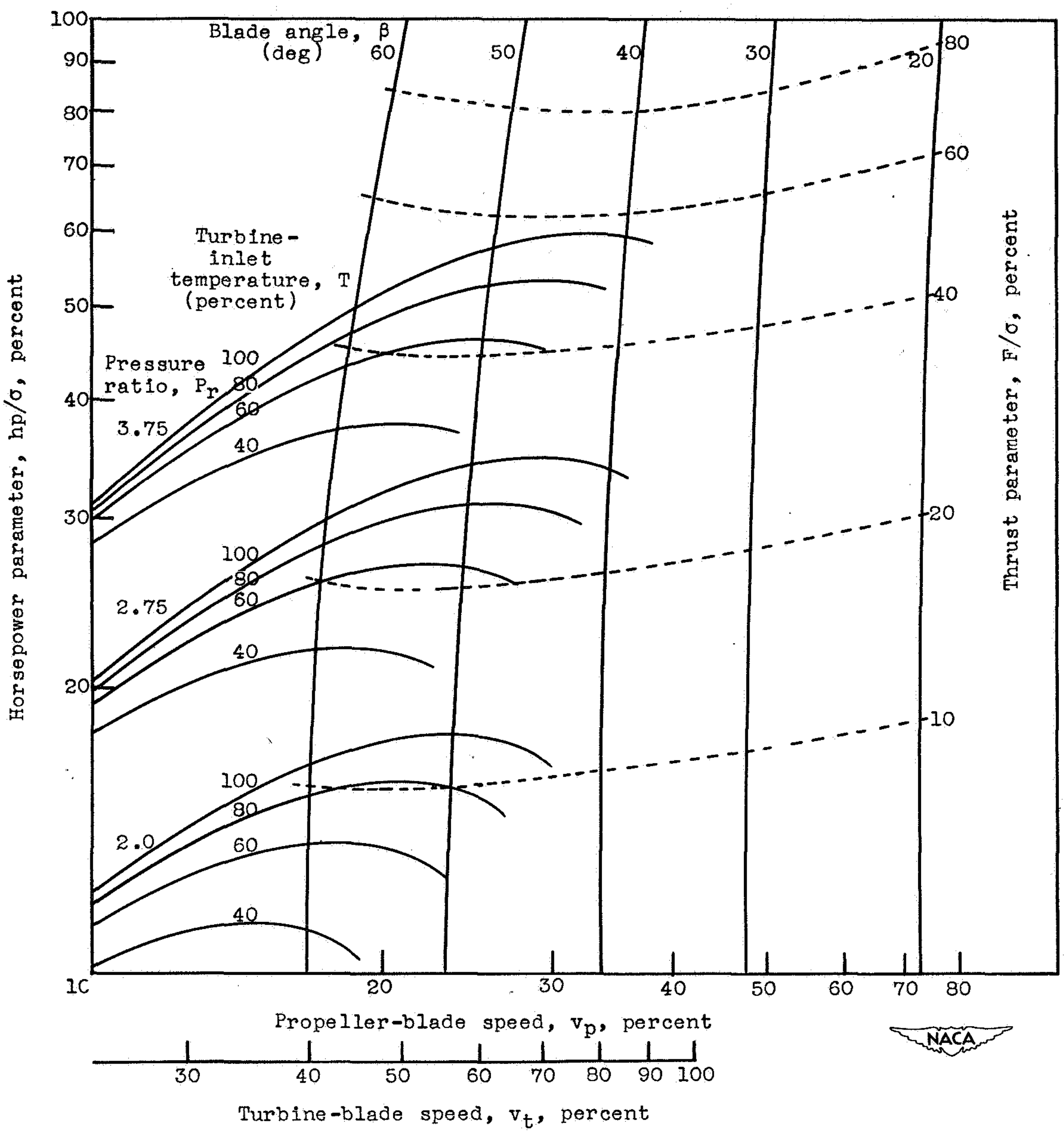
(c) Altitude, sea level; flight velocity, 600 miles per hour.

Figure 5. - Continued. Performance characteristics of independent turbine-propeller combination.



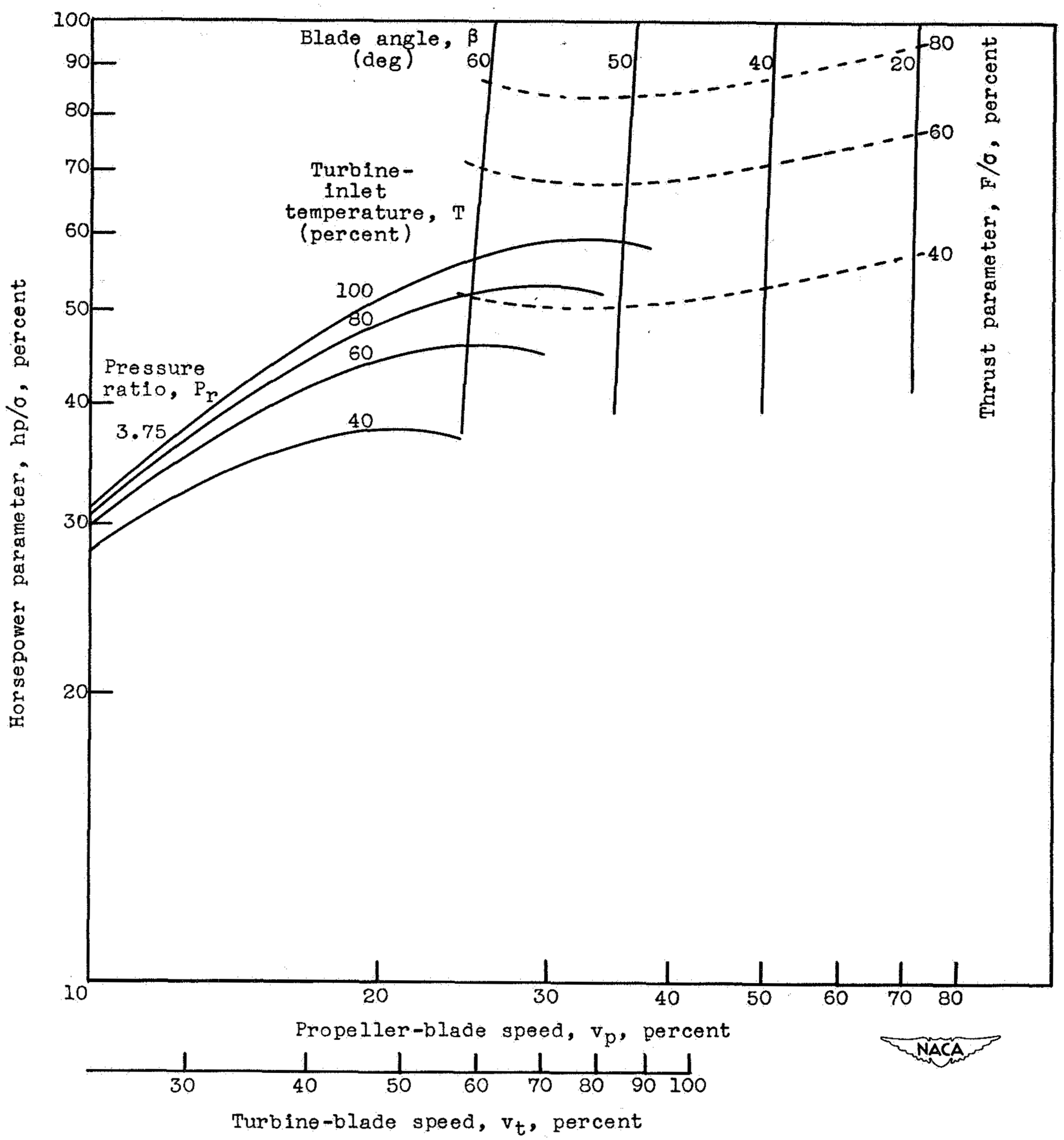
(d) Altitude, 40,000 feet; flight velocity, 200 miles per hour.

Figure 5. - Continued. Performance characteristics of independent turbine-propeller combination.



(e) Altitude, 40,000 feet; flight velocity, 400 miles per hour.

Figure 5. - Continued. Performance characteristics of independent turbine-propeller combination.



(f) Altitude, 40,000 feet; flight velocity, 600 miles per hour.

Figure 5. - Concluded. Performance characteristics of independent turbine-propeller combination.

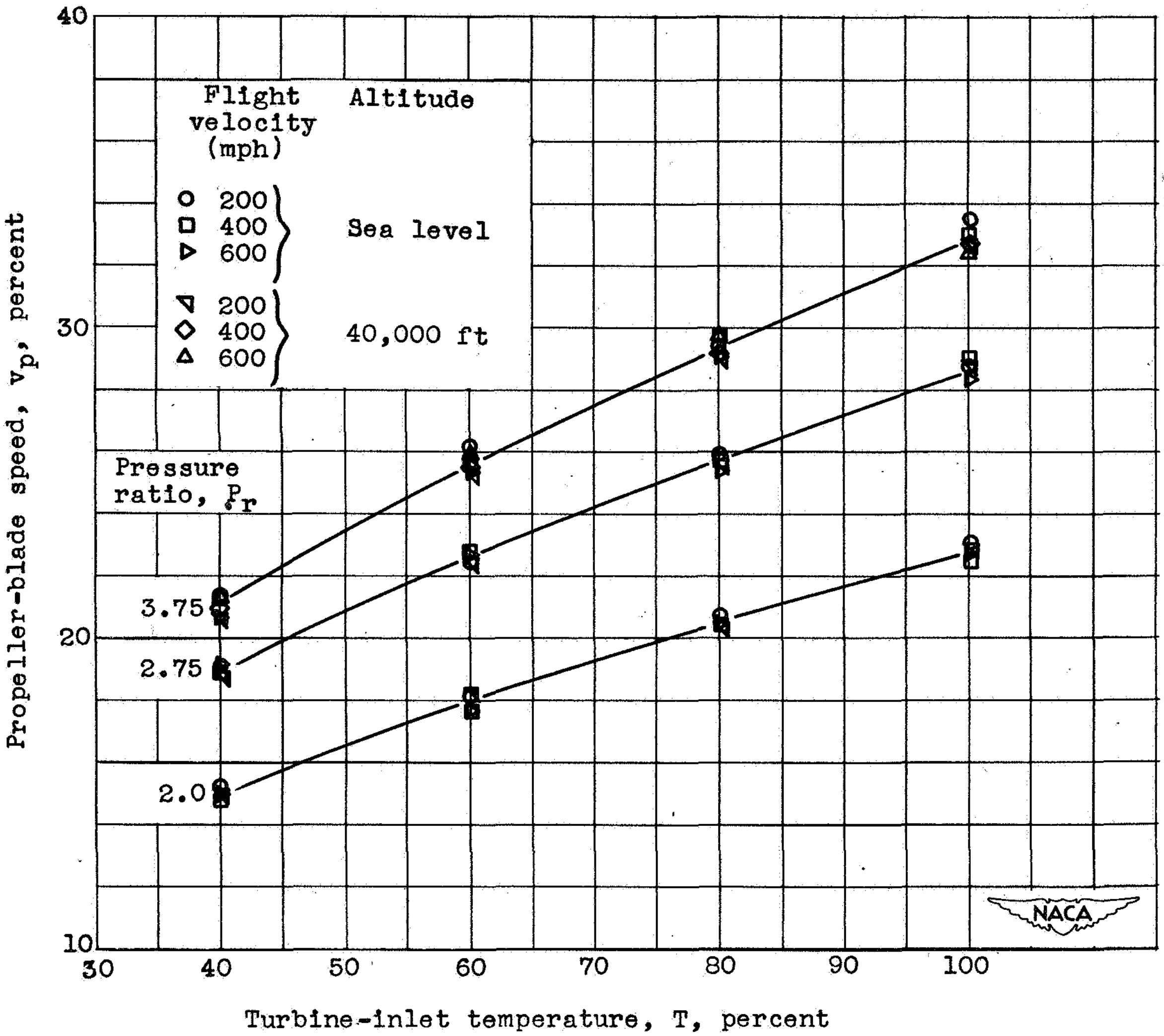


Figure 6. - Control relation for maximum operating efficiency of independent turbine-propeller combination.